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STUDY TO DETERMINE THE UTILITY OF SPECTRUM TO DOSE CONVERSION

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FINAL REPORT

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INTRODUCTION

For many years attempts have been made to measure physical dose (energy deposited per unit mass) in radiation fields in order to relate and predict radiation effects. For simplicity, developments have tended toward integrating devices so that a single number, dose, could be read directly from the device. Direct reading dosimeters are usually based on ionization measurements and have utilized both ionization chambers and solid state detectors. The reliability of the measurements from these devices is dependent upon the assumption that the system is wholly responsive to energy deposited, exclusive of radiation quality and/or the equivalence of the calibration and measured fields. These devices yield a single value, physical dose, which when applied to biological effect, must be converted to biological dose. Since it is generally accepted that biological dose is a function of radiation type and energy, no relationship can be established between a measured physical dose and a biological dose unless the radiation types and spectra are considered. No system is currently available which does distinguish particle type and spectra and yield a direct dose readout.

It is the purpose of this effort to demonstrate the utility of the LTV pulse height to dose conversion system, in conjunction with the LTV Beta-Gamma Spectrometer, as such a system. The Beta-Gamma Spectrometer was developed by LTV for the Manned Spacecraft Center (NASA) in Houston, Texas, under Contract No. NAS9-5765[1]. This effort will also provide a conceptual electronic design of a system utilizing the Beta-Gamma Spectrometer as a real time dosimeter for separate or mixed fields of both electrons and gamma rays.

I. GENERAL METHOD OF APPROACH

In order to utilize the Beta-Gamma Spectrometer as a direct reading real time dosimeter, it is necessary to convert the pulse-height spectra to physical or biological dose. The conventional method of approach would be to first reduce each pulse-height spectrum to an energy spectrum and then apply energy-to-dose conversion numbers to the energy spectrum. The total dose would then be given as the sum of the doses from each energy channel of the spectrometer. To take this route requires the use of the spectrometer's response matrix R or the inverse of this matrix R^{-1} in order to arrive at the energy spectrum. The storage and application of R or R^{-1} requires use of an onboard computer if the dose is being metered in a spacecraft.

In order to avoid the problems of storing and using a large matrix on board a spacecraft, an alternate method has been developed by LTV. This method still utilizes a radiation spectrometer as the dosimeter, but eliminates the need for R or R^{-1} to be stored and used in a computer. The new method relies on the determination of a simple function which is immediately used to convert the pulse-height information into dose. An explanation of this approach using matrix algebra is as follows.

A dose spectrum D may be related to a source spectrum S by the following matrix equation,

$$D = CS, \tag{1}$$

where C is a diagonal matrix representing the dose per unit flux as a function of energy for a specific type of radiation with geometrical effects taken into account. The source spectrum S is related to the pulse-height spectrum P from the radiation spectrometer by the following equation,

$$P = RS, \tag{2}$$

where R represents the response function of the spectrometer. Solving for S gives,

$$S = R^{-1}P. \tag{3}$$

Combining equations (1) and (3) gives,

$$D = CR^{-1}P. \tag{4}$$

The matrix product CR^{-1} may be taken first giving,

$$D = FP, \tag{5}$$

where

$$F = CR^{-1}. \tag{6}$$

Since C and R may be determined experimentally, the matrix F is determined. Now the dose spectrum D is not required, only the total dose. Letting $D = [d_{ij}]$ then the total dose is given as $\sum_{j=1}^{n} [d_{ij}]$ where D is an mxn row matrix, i.e., $m = 1$. Denoting the total dose as x, we have

$$x = \sum_{j=1}^{n} [d_{ij}], \tag{7}$$

Now letting $F = [f_{ij}]$ and $P = [p_{ij}]$, we have

$$x = \sum_{i=1}^{m} [f_{ij}]_{\,j=1,n}\, [p_{ij}] \tag{8}$$

where the expression $\sum_{i=1}^{m} [f_{ij}]_{\,j=1,n}$ represents the function, f, that converts the pulse-height spectrum to dose. As previously mentioned it is entirely experimentally determined and contains only the square root of the number of terms in R due to the summation over the rows for each column of F.

II. DERIVATION OF THE PULSE HEIGHT TO DOSE FUNCTIONS

The initial phase of the analytical program was to verify the validity of the response matrices for the β-γ spectrometer. These matrices, both electron R_e and gamma R_γ, were presented in Reference 1, as the product of a diagonal efficiency matrix ε and a normalized resolution matrix, which we shall denote here as N. Inspection of these matrices revealed no significant errors. They were used in the present study in their previous form except for one modification. In the previous presentation all of the detector responses were extrapolated below the electronic cut-off down to zero pulse height and the efficiencies ε_e and ε_γ were reported accordingly. For the present work the responses N were renormalized, omitting the region below 100 keV to eliminate the uncertainty introduced by the extrapolation. The adjusted efficiencies are shown in Tables 1 and 2. The entries in the Tables represent the non zero elements of the diagonal efficiency matrices. The dimensions of the response matrices are 15 X 15 with N_γ extending over the range from 0.1 to 3.1 MeV and N_e from 0.3 to 3.3 MeV. The response bin widths are 200 keV for both matrices. The inversion to obtain N_γ^{-1} and N_e^{-1} was accomplished with the aid of an IBM 7090 matrix inversion routine, which was shown to give results accurate to three and sometimes four significant figures. As a preliminary test the normalized inverse matrices were multiplied by the pulse-height spectra which were taken on the β-γ spectrometer and found to conserve the total number of electrons or photons in the input data. This is a property which is expected when using a normalized matrix. The inversion of ε_γ and ε_β were trivial, since the inverse of a diagonal matrix is formed by taking the reciprocal of each element. The flux to dose conversion values C_e and C_γ were obtained from the literature[2,3] and are shown in Table 3 and Table 4 respectively. These values are consistent with those being used in the national laboratories. Gamma conversion to roentgen exposure dose was used to allow comparison with the R-Meter measurements to be discussed later. The electron conversion chosen was to rad in carbon, which is the most common absorbed dose reference. At this point the actual dose unit is irrelevant and any one may be used to satisfy a given requirement.

The above matrices were then multiplied to give the products $N_e^{-1}\,\varepsilon_e^{-1}\,C_e$ and $N_\gamma^{-1}\,\varepsilon_\gamma^{-1}\,C_\gamma$ which correspond to F_e and F_γ respectively. Each column of

TABLE 1

GAMMA EFFICIENCIES

E (MeV)	ε_γ (counts/photon/cm^2)
0.2	0.638*
0.4	0.463
0.6	0.537
0.8	0.541
1.0	0.500
1.2	0.529
1.4	0.486
1.6	0.565
1.8	0.575
2.0	0.567
2.2	0.560
2.4	0.558
2.6	0.560
2.8	0.563
3.0	0.600

* These values were obtained by integrating over 200 keV intervals with the indicated energy representing the midpoint of the interval. This applies also to Tables 2, 3, and 4.

TABLE 2

ELECTRON EFFICIENCIES

E (MeV)	ε_e (counts/electron/cm^2)
0.4	0.832
0.6	0.891
0.8	0.830
1.0	0.791
1.2	0.798
1.4	0.838
1.6	0.862
1.8	0.863
2.0	0.857
2.2	0.842
2.4	0.828
2.6	0.821
2.8	0.820
3.0	0.820
3.2	0.820

TABLE 3

ELECTRON SPECTRUM TO DOSE CONVERSION VALUES

E(MeV)	C_e (rad/electron/cm^2)
0.4	3.06(-8)
0.6	2.83(-8)
0.8	2.74(-8)
1.0	2.70(-8)
1.2	2.69(-8)
1.4	2.69(-8)
1.6	2.70(-8)
1.8	2.72(-8)
2.0	2.74(-8)
2.2	2.75(-8)
2.4	2.77(-8)
2.6	2.78(-8)
2.8	2.80(-8)
3.0	2.82(-8)
3.2	2.84(-8)

TABLE 4

GAMMA SPECTRUM TO DOSE CONVERSION VALUES

E (MeV)	C_γ (roentgen/gamma/cm^2)
0.2	1.04(-10)
0.4	2.31(-10)
0.6	3.42(-10)
0.8	4.45(-10)
1.0	5.42(-10)
1.2	6.12(-10)
1.4	7.00(-10)
1.6	7.64(-10)
1.8	8.42(-10)
2.0	9.01(-10)
2.2	9.59(-10)
2.4	1.02(-9)
2.6	1.08(-9)
2.8	1.14(-9)
3.0	1.20(-9)

these two matrices was summed over the rows to give the pulse height to dose conversion functions f_e and f_γ. Each function contains 15 terms. f_e and f_γ are shown in Table 5 and Table 6 respectively. Inspection of these functions reveals not only an erratic nature, but some of the values are even found to be negative. This seems to be characteristic of the solutions of matrix equations where the inverse is used to solve for an unknown matrix. This characteristic comes about from several causes:

(a) uncertainties in the response matrix,

(b) nature of the inverse (many negative terms),

(c) tendency of the inverse to magnify small fluctuations, and

(d) finite number of terms in the matrix (grid size).

After a detailed inspection verified the accuracies of the matrices and their inverses, an alternate approach was taken to determine f. The method is based on the equation

$$F = N^{-1} \varepsilon^{-1} C. \tag{9}$$

If we multiply both sides by N we get

$$NF = NN^{-1} \varepsilon^{-1} C \tag{10}$$

or

$$NF = \varepsilon^{-1} C. \tag{11}$$

If we use C as a column matrix composed of the non zero elements of the original C matrix, then F becomes a column matrix equivalent to the function f. This equation lends itself to a solution using a standard iterative process as follows. Equation 11 says that there exists a function (or matrix) F that, when multiplied by the response matrix N, gives $\varepsilon^{-1} C$. Since $\varepsilon^{-1} C$ is well known and N is well known, by making an intelligent estimate of F (which we will refer to as F_1) and multiplying the estimate by N, it is possible to compare the result with $\varepsilon^{-1} C$. The degree of agreement between NF_1 and $\varepsilon^{-1} C$ is a direct measure of the degree of agreement between F_1 and F. Thus, by successively correcting F_1 by the difference between NF_1 and $\varepsilon^{-1} C$ and remultiplying the corrected F_1 (F_2, F_3, etc.) by N, an iterative method is arrived at which generates a function F_n which approaches F when $(NF_n - \varepsilon^{-1} C) = 0$. Since it is known that the response functions N_e and N_γ are such that the pulse-height and true energy spectra are not drastically different, the first estimate of F for

TABLE 5

PULSE HEIGHT TO DOSE CONVERSION FOR ELECTRONS

DERIVED FROM ELECTRON RESPONSE INVERSE

E(MeV)	f_e(rad/count)
.4	3.68(-8)
.6	2.82(-8)
.8	4.32(-8)
1.0	-1.20(-8)
1.2	1.37(-7)
1.4	-6.96(-8)
1.6	1.24(-7)
1.8	-5.73(-8)
2.0	1.25(-7)
2.2	-6.49(-8)
2.4	1.28(-7)
2.6	-4.45(-8)
2.8	1.01(-7)
3.0	-2.51(-8)
3.2	8.68(-8)

TABLE 6

PULSE HEIGHT TO DOSE CONVERSION FOR GAMMAS

DERIVED FROM GAMMA RESPONSE INVERSE

E(MeV)	f_γ (roentgen/count)
0.2	2.21(-10)
0.4	6.32(-10)
0.6	1.24(-9)
0.8	1.36(-9)
1.0	1.40(-9)
1.2	8.68(-10)
1.4	2.16(-9)
1.6	2.97(-9)
1.8	1.91(-10)
2.0	3.08(-9)
2.2	5.28(-9)
2.4	2.65(-9)
2.6	-1.32(-9)
2.8	4.59(-9)
3.0	1.63(-8)

each radiation was taken as the respective ε^{-1} C. Throughout the iterations NF_n was compared to ε^{-1} C on an R.M.S. basis with the average R.M.S. difference computed after each iteration. When the average R.M.S. difference reached a minimum the computation was stopped. The function determined for the gammas had an R.M.S. difference of 1.2% while the same for the electrons was 2.6%. The gamma distributions converged on the 26th iteration while the electron distribution converged on the 6th. The resulting functions were then smoothed with a three point average routine. The final matrices which represent the f functions are shown in Table 7 (electrons) and Table 8 (gammas). A plot of these functions is shown in Figs. 1 and 2. It is seen that these functions are smoothly varying and non-negative. This is the result of working directly with N_e and N_γ instead of their inverses.

TABLE 7

PULSE HEIGHT TO DOSE CONVERSION FOR ELECTRONS

DERIVED BY ITERATIVE METHOD

E(MeV)	f_e(rad/count)
0.4	3.68(-8)
0.6	3.02(-8)
0.8	3.45(-8)
1.0	3.46(-8)
1.2	3.61(-8)
1.4	3.20(-8)
1.6	3.00(-8)
1.8	3.00(-8)
2.0	3.17(-8)
2.2	3.18(-8)
2.4	3.31(-8)
2.6	3.44(-8)
2.8	3.96(-8)
3.0	4.10(-8)
3.2	4.21(-8)

TABLE 8

PULSE HEIGHT TO DOSE CONVERSION FOR GAMMAS

DERIVED BY ITERATIVE METHOD

E(MeV)	f_γ(roentgen/count)
0.2	2.21(-10)
0.4	6.32(-10)
0.6	1.24(-9)
0.8	1.37(-9)
1.0	1.47(-9)
1.2	1.55(-9)
1.4	1.75(-9)
1.6	1.83(-9)
1.8	2.04(-9)
2.0	2.33(-9)
2.2	2.62(-9)
2.4	3.05(-9)
2.6	3.56(-9)
2.8	4.52(-9)
3.0	6.06(-9)

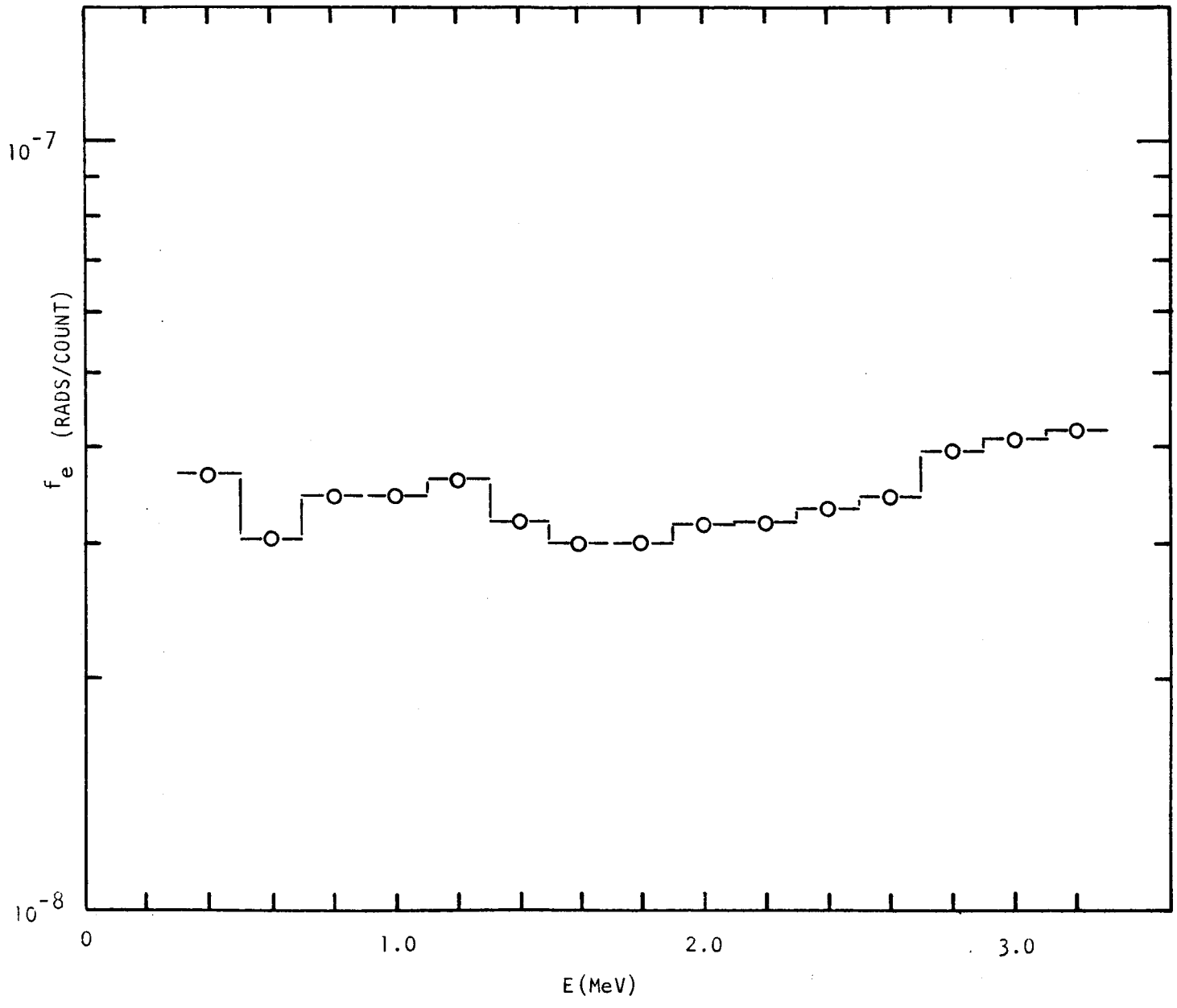


FIGURE 1 Pulse Height to Dose Function for Electrons

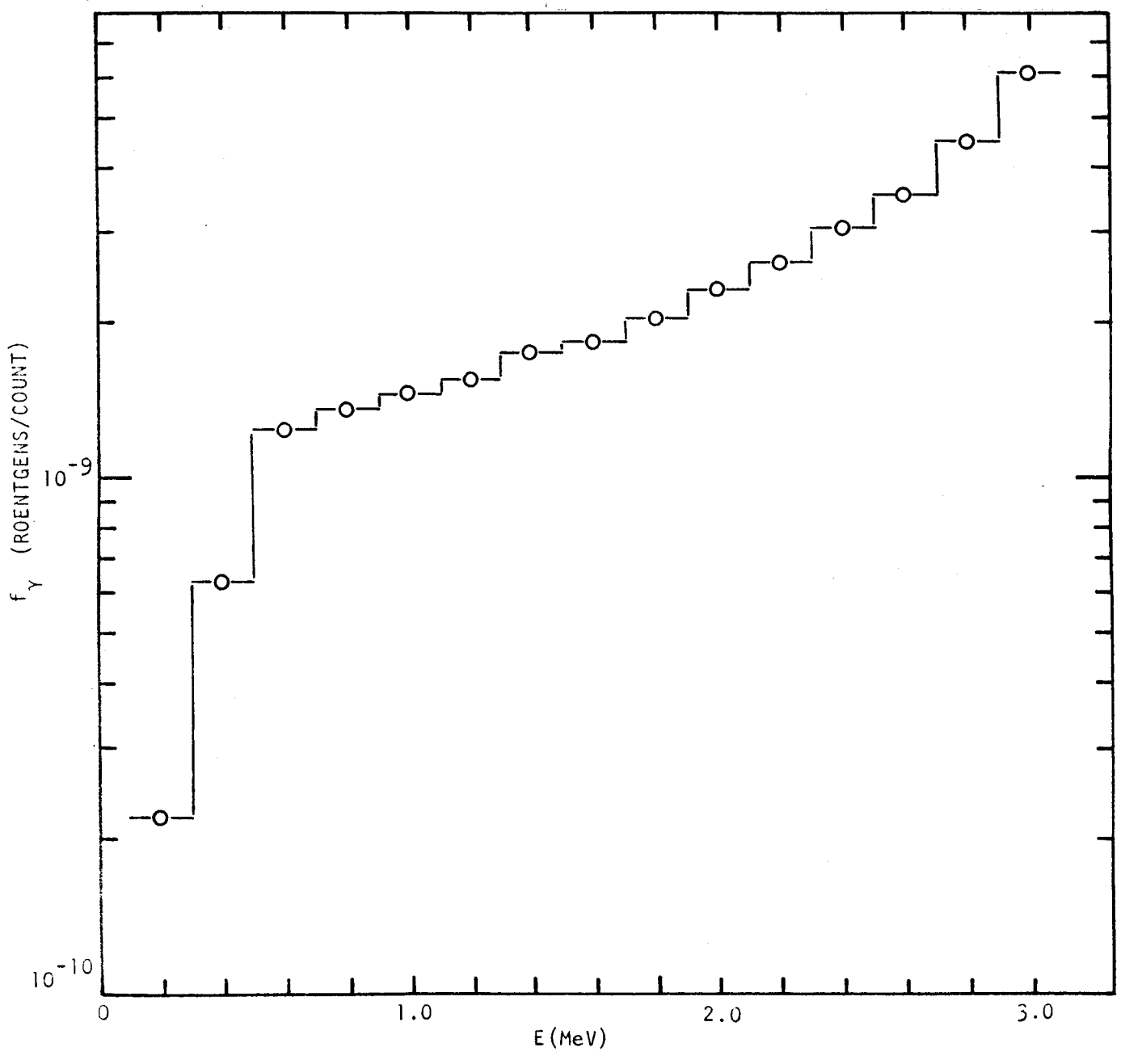


FIGURE 2 Pulse Height to Dose Function for Gammas

III. VERIFICATION OF THE PULSE HEIGHT TO DOSE FUNCTIONS

1. Comparison of β-γ Spectrometer Measurements to Calculated Dose

In support of the uniqueness of these two functions or their resemblance to the true values, it is of interest to compare f_e and f_γ derived by the iterative method to those derived by the matrix inverse method. This is done in Figs. 3 and 4. It is seen that the values obtained by the iterative method do indeed resemble those of the inverse method to the extent of approaching a least squares fit or a smoothing of the erratic functions. The only other test is to apply the final functions to pulse-height spectra and compare to an independent theoretically or experimentally determined dose. This was done for monoenergetic electrons, monoenergetic gamma rays, and an x-ray spectrum. For the monoenergetic radiations a pulse-height spectrum was accumulated on the β-γ spectrometer. The true dose was determined from a prior calibration of the source (in the case of the gammas), which yielded the total flux incident on the spectrometer, and applying the flux to dose conversion value at that energy. For the electrons the flux was determined with solid state silicon detectors, as discussed by Rester and Rainwater[4,5]. The x-ray spectrum used was that measured by Rester, Dance, and Baggerly[6,7], using a Trail and Raboy type anticoincidence NaI spectrometer. This spectrum was converted to dose by multiplying by the energy-to-dose function. Measurements in an identical geometry were made with the β-γ spectrometer. The doses corresponding to the above measurements were then determined by multiplying the pulse-height distributions from the β-γ spectrometer by f_e and f_γ and summing. For example, the total counts in the pulse-height spectrum from 0.1 to 0.3 MeV were multiplied by the value of f_γ at 0.2 MeV, etc. The results for both the electrons and gammas are shown in Tables 9 and 10 respectively. It is seen that for the electrons the agreement is better than 10% in all cases. For the gammas all points but one are within 10%. This is considered good agreement as there are several factors which can contribute to errors of the order of 2 or 3 percent. These include the calibration errors of the β-γ spectrometer, the NaI spectrometer, and of the sources themselves. The fact that all of the monoenergetic data is low compared to the calculated dose suggests that a systematic error was encountered in the analysis. This could be corrected by increasing f_e and f_γ by an amount which would result in measured doses which fluctuated about the true dose. For the present analysis this would require about a 5 percent increase.

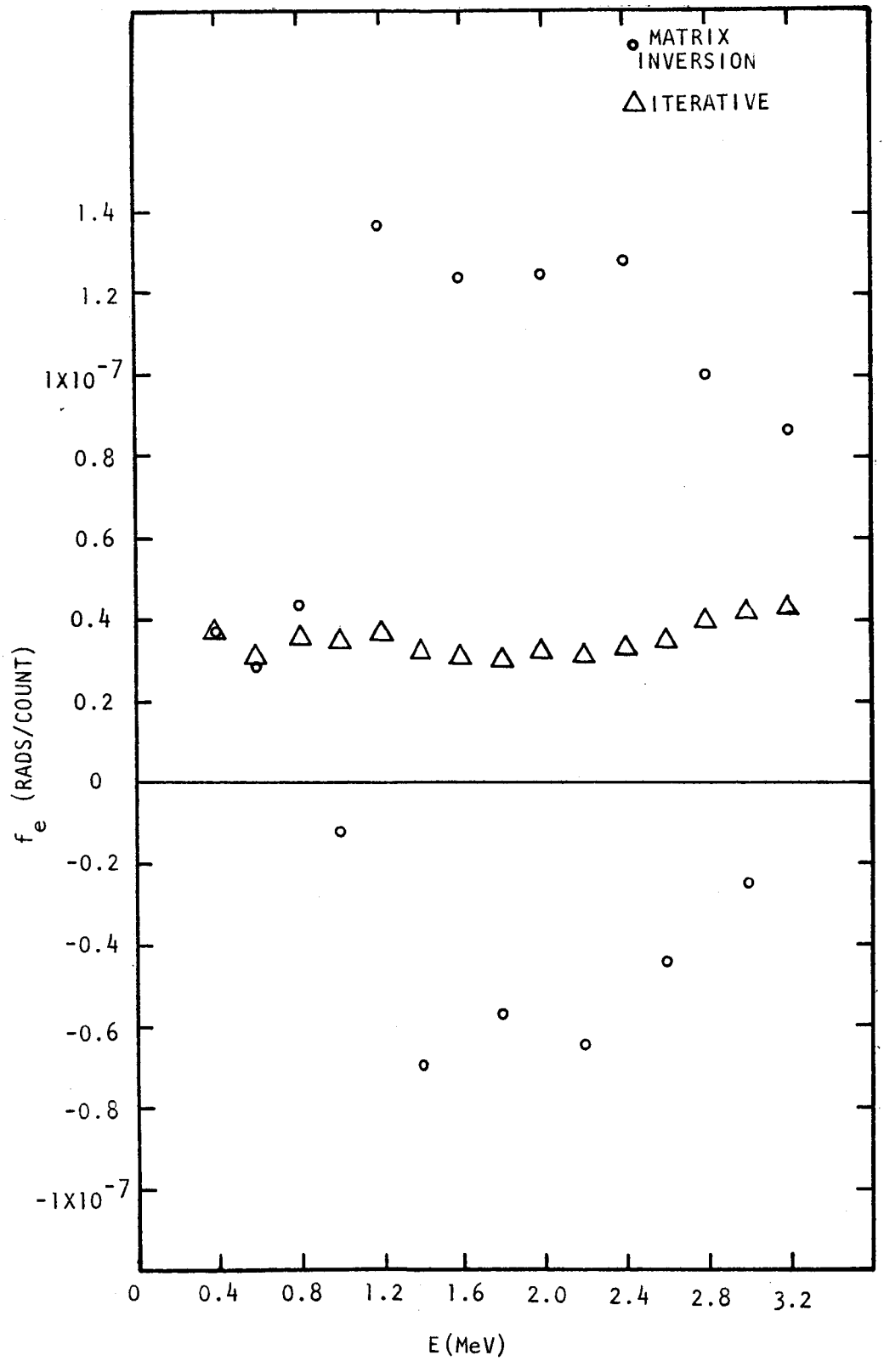


Figure 3 Comparison of Pulse Height to Dose Functions for Electrons

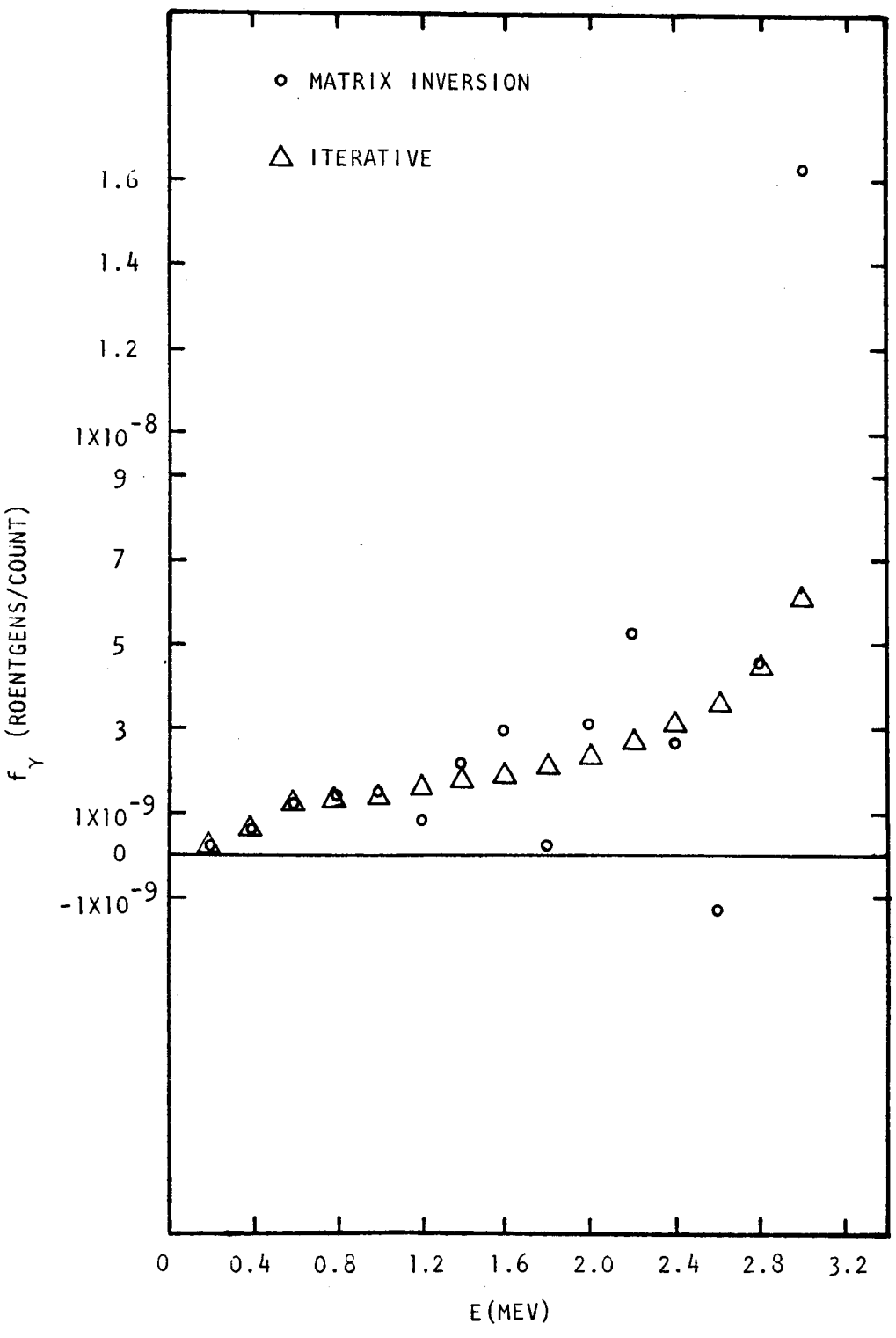


Figure 4 Comparison of Pulse Height to Dose Functions for Gammas

TABLE 9

RESULTS OF APPLYING f_e TO

MONOENERGETIC ELECTRONS

E(MeV)	True Dose (Rad)	Measured* Dose (Rad)	Percent Error
0.40	7.47(-3)	7.06(-3)	-5.5
0.50	7.06(-3)	6.93(-3)	-1.8
0.75	6.62(-3)	6.61(-3)	-0.1
1.00	6.43(-3)	6.32(-3)	-1.7
1.25	6.35(-3)	6.06(-3)	-4.6
1.50	6.32(-3)	5.85(-3)	-7.4
2.0	5.28(-3)	5.18(-3)	-1.8
2.5	3.05(-3)	2.90(-3)	-4.9

* Measurements made with β-γ spectrometer and reduced to dose using f_e.

TABLE 10

RESULTS OF APPLYING f_γ TO MONOENERGETIC GAMMAS AND A BREMSSTRAHLUNG SPECTRUM

Source	Energy	True Dose (R)	Measured Dose (R)*	Percent Error
Cs^{137}	0.662	1.14(-4)	1.04(-4)	-8.0
Mn^{54}	0.835	1.17(-4)	1.17(-4)	0.0
Hg^{203}	0.279	8.23(-5)	7.72(-5)	-6.1
Na^{22}	1.28	1.85(-4)		
	0.511	1.62(-4)		
		3.47(-4)	3.10(-4)	-10.7
Y^{88}	0.9	8.50(-5)		
	1.8	17.00(-5)		
	2.76	.12(-5)		
		2.56(-4)	2.26(-4)	-12.0
X-Ray Spectrum	2.0**	4.40(-5)	4.66(-5)	+ 6.1

* Measurements made with β-γ spectrometer and reduced to dose using f_γ.

** End point energy of the spectrum

Thus, the iterative method of deriving f_γ and f_e appears to give a more physically meaningful function than the inverse method and the functions, when applied to pulse-height spectra, give answers within the expected accuracy. Though this method is considered adequate in approaching the problem it is not felt that the inverse method should be discarded, but should be used to further substantiate the iterative method.

2. Comparison of Victoreen R-Meter to Calculated Dose

As a further check on the accuracy of the calculated doses, Victoreen R-Meters were used to measure the electron and gamma doses. The electrons were monitored with a thin walled (7 mg/cm^2) electron probe (#576). The gamma sources were monitored with Victoreen probe #633. The gamma probe is used internationally as a secondary standard. The measurements obtained with the electron probe were the first absolute numbers generated on this device according to private communications with the Victoreen Instrument Company.

Electron Measurements

The experimental setup is shown in Fig. 5. A narrow beam of electrons was diffused with a 2, 3, 4, or 5 mil aluminum foil designated as the main diffuser. This range of thicknesses was required as the accelerator potential was varied from 0.5 to 1.7 MeV. The diffused beam then passed thru a 2 mil secondary diffuser into air. At this point the beam was approximately 2 inches in diameter. After penetrating approximately one foot into air the beam was mapped with a solid state detector and found to be uniform in intensity for a distance of 2 inches on either side of centerline. At this position readings were obtained with the thin walled electron probe #576 and compared with the integrated flux from a solid state detector. The dose per electron per cm^2 was obtained as a function of incident electron energy. To insure that a significant number of electrons was not being scattered into the Victoreen probe, the measurements were repeated without the presence of the solid state detector. This was accomplished by relating the incident flux to the flux at a detector monitoring the backscattered electrons from the main diffuser. The results of this calibration are plotted in Fig. 6 along with the theoretical flux to dose curve for muscle[2,8]. The Victoreen probe is designed as a skin equivalent device and reads directly in rad. It is seen that this thin walled probe does

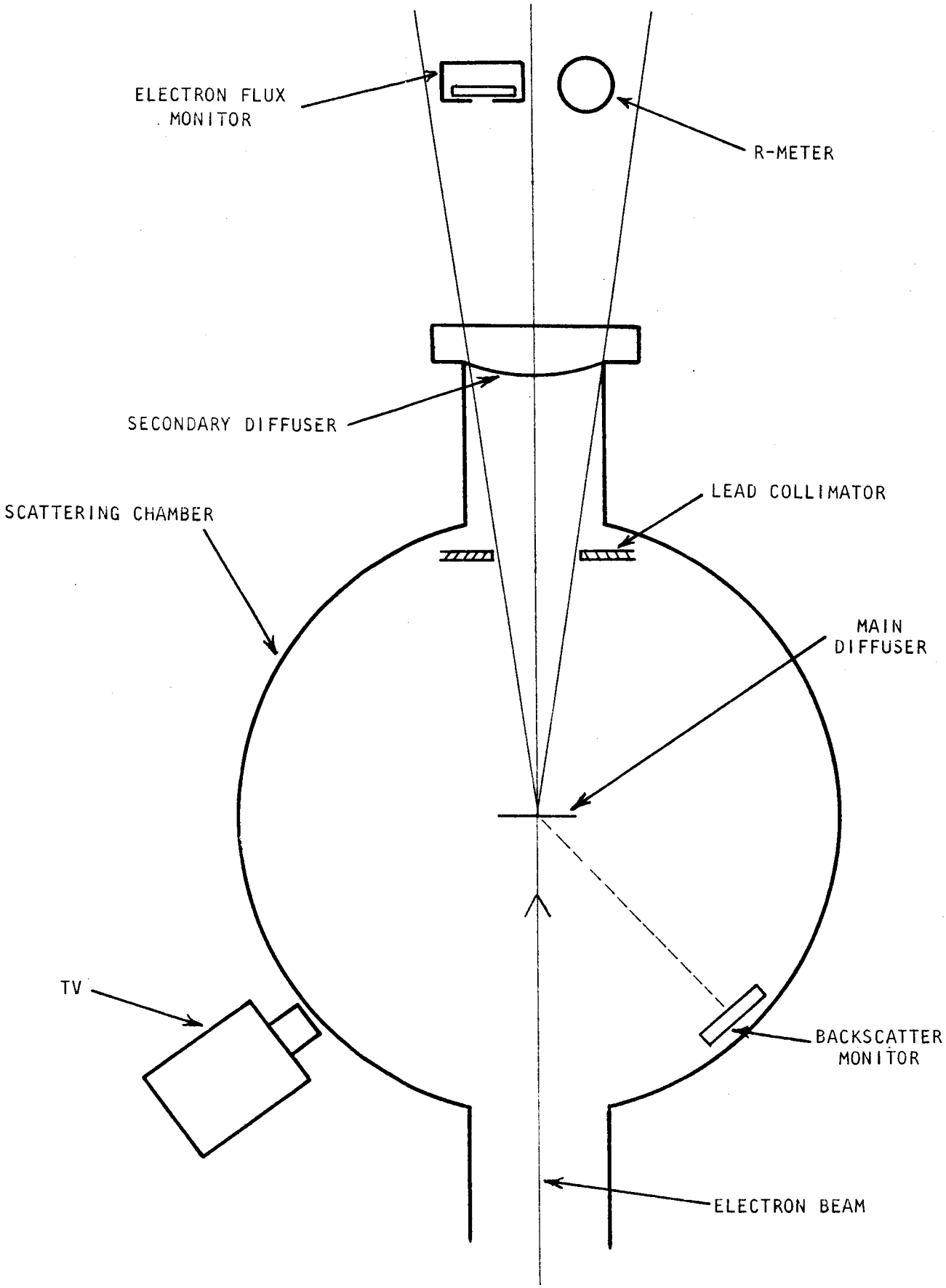


FIGURE 5 Experimental Setup for Electron Calibration

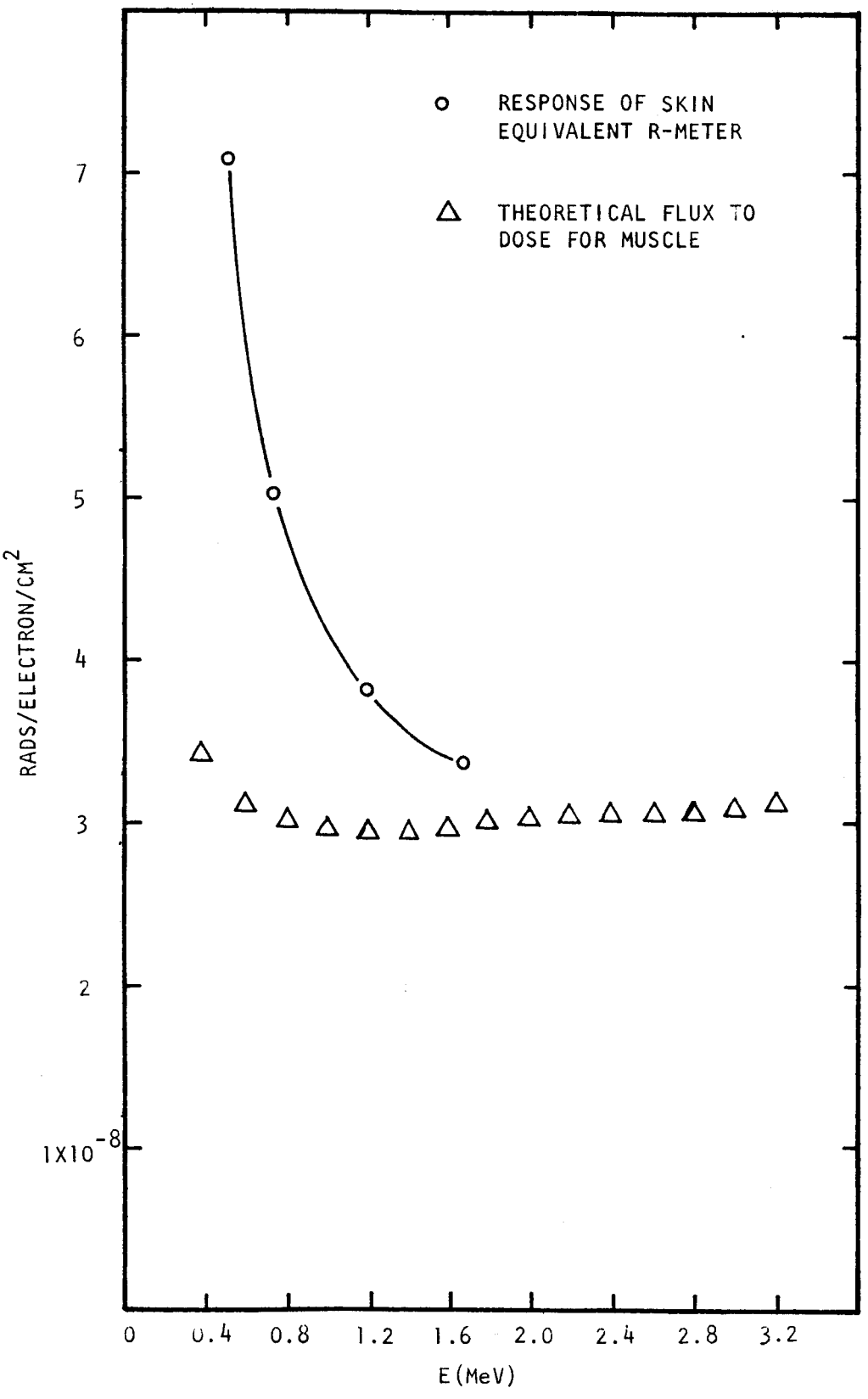


FIGURE 6 Response of Victoreen R-Meter (Probe #576) to Monoenergetic Electrons

not agree well with the theoretical values in the energy range covered. It is felt that the discrepancy is due to the longer path that lower energy electrons are permitted to travel after being scattered at large angles in the cylindrically shaped probe whose length is several times its diameter. Above 2.0 MeV, where scattering is reduced, it appears that the curves are converging and bear out the measurements with the solid state detectors and the flux to dose conversion factors very well.

Gamma Measurements

Three of the sources used for the gamma-ray measurements with the β-γ spectrometer were monitored with Victoreen R-Meter #633. The sources used were Co^{60}, Na^{22}, and Cs^{137}. The calibrated Hg^{203} source had decayed below the level necessary to obtain a meaningful dose measurement. The measurements with the other sources were obtained in air at distances of one and two feet and found to agree with the calculated values to better than 6 per cent in all cases. This was considered to be good agreement, since the probe is quoted as a 10 per cent device. Recent studies by this group indicate that the Victoreen series of probes is not best suited for low dose rates. For these measurements the dose rates varied from 10 to 40 milliroentgen per hour. Exposure times were of the order of days. For these long exposures it has been suggested that a probe such as that built by Professor Frank Shonka at Saint Procopious College would be less likely to exhibit leakage which was not associated with the source radiation. This probe is currently under investigation.

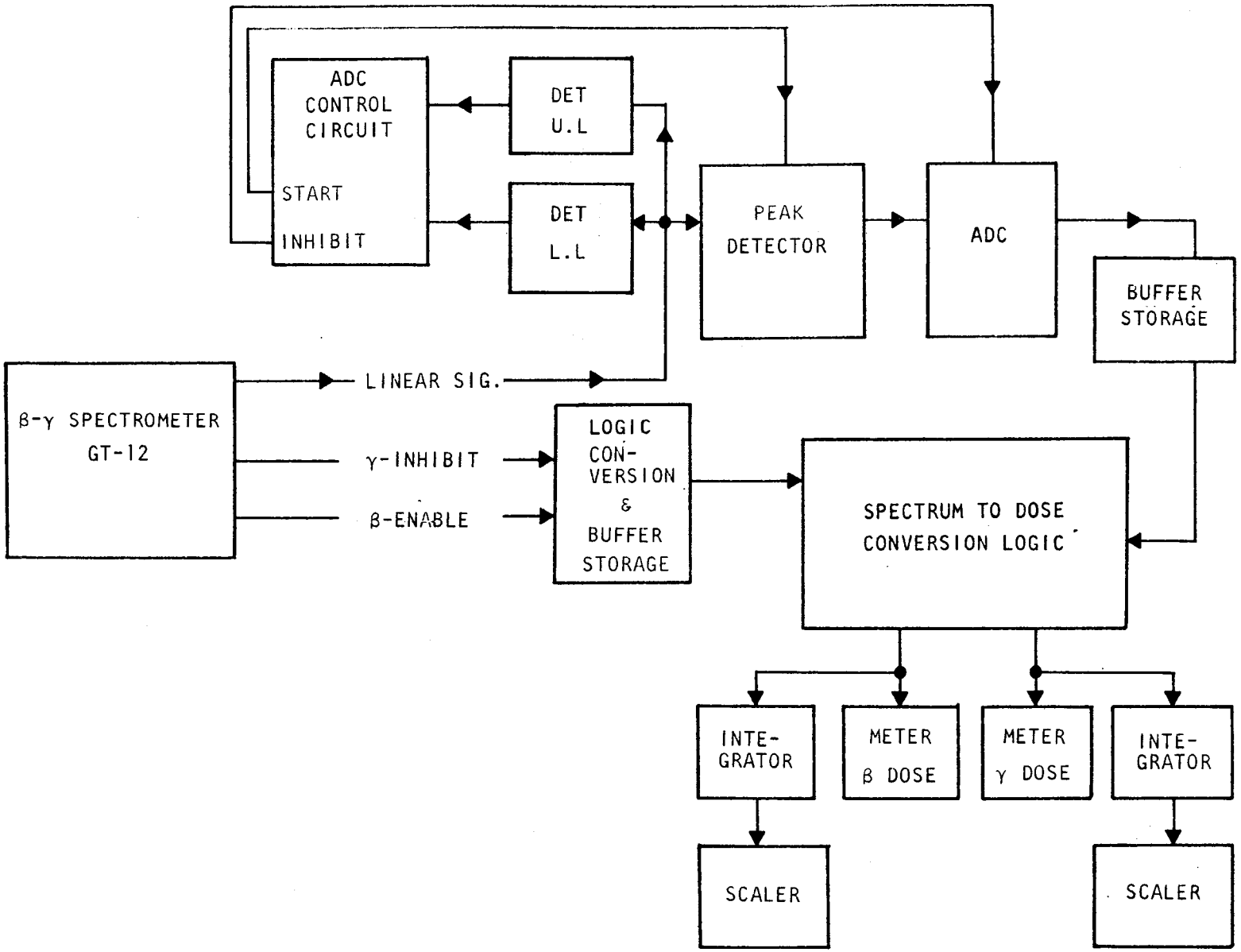
IV. ELECTRONIC DESIGN

In the previous sections it has been shown that the pulse-height spectrum-to-dose conversion technique is not only feasible, but also very accurate. In addition, computer techniques have been developed to provide the necessary spectrum-to-dose conversion functions. However, to demonstrate the unit as a real-time device, an electronic conversion and read-out system will be required.

As a part of this study, several concepts were considered for the conversion involving both analog and digital methods. Because of simplicity and versatility a digital system was chosen and several components of the system were constructed and studied in breadboard form. A conceptual design for a complete system was made using the β-γ spectrometer as the sensing head. The system may be best described by referring to the block design in Fig. 7. Since the linear signal output of the β-γ spectrometer must be converted to digital levels or channels, an analog to digital converter that has adjustable channel widths will be required. The signal level will be detected by a peak detector and held at the peak level until the ADC has completed its cycle. ADC start and inhibit pulses will be formed by lower and upper level detectors so that noise and excessive amplitude pulses will not be analyzed. The output of the ADC and particle type logic level will be stored in a buffer register. When the next pulse is being analyzed the spectrum-to-dose conversion circuitry will convert the stored data to a pulse of constant amplitude, but with a width which is proportional to the dose value for a particular energy and particle. The newly analyzed pulse will then be transferred into the buffer register awaiting the next particle pulse for dose conversion. This method will significantly reduce the dead time of the instrument. The dose pulses from both the beta and gamma channels will then be applied to a variable range voltmeter for dose rate display. In order to read integrated dose a digital integrator circuit will convert the total dose to a series of pulses that will be counted by a scaler.

This system will provide the capability for measurements in separate or mixed beta and gamma fields and provide both dose rate and total dose measurements.

FIGURE 7 Block Diagram of Electronics



CONCLUSIONS

It is felt that this study has sufficiently demonstrated the feasibility of the proposed method for converting pulse-height spectra to dose, in as much as the method prescribed was carried out on an actual space qualified instrument and results were found to be accurate to within the limits of normal experimental errors. The method can easily be applied to any type of radiation and geometrical configurations, if a suitable experimental or theoretical calibration of the spectrometer can be obtained. With this approach a simple electronic circuit, as discussed earlier, can be designed, which will accomplish the conversion and avoid the necessity of an onboard computer.

The next phases of this program will include the demonstration of the device as a real-time dosimeter, followed by analytical studies to include complex geometrical arrangements and depth dose calculations, and finally the design of a truly versatile sensor head using solid state detectors for electrons, gammas, and protons.

LIST OF REFERENCES

1. Farmer, B. J., Chappell, N. E., Bagwell, R. G., and Rainwater, W. J., "LTV Beta-Bremsstrahlung Spectrometer for Gemini XII", Contract No. NAS9-5765 Final Report, March 1967.

2. Nelms, A. T., "Energy Loss and Range of Electrons and Positrons", National Bureau of Standards Circular 583, 1957.

3. Rockwell III, Theodore, "Reactor Shielding Design Manual", McGraw-Hill Book Co., Inc., 1956.

4. Rester, D. H. and Rainwater, Jr., W. J., Nucl. Instr. and Meth. 41 (1966)51.

5. Rester, D. H. and Rainwater, Jr., W. J., Phys. Rev. 140, 1A(1965).

6. Dance, W. E., Baggerly, L. L., Rester, D. H., and Rainwater, Jr., W. J., "Investigation of Electron Interactions with Matter", NASA CR-334, December 1965.

7. Rester, D. H., Rainwater, Jr., W. J., and Dance, W. E., "Investigation of Electron Interaction in Matter", Final Report Contract NAS8-21055, February 1968.

8. NBS Handbook 85, "Physical Aspects of Irradiation", March 1964.